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13. ABSTRACT (Maximum 200 words)

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A study of the optical properties has begun in which the structures are characterized by room temperature and 2K photoluminescence and photocurrent spectroscopies. Responsivity curves for structures having various well shapes have shown the excited states and a comparison with theory is in progress. A preliminary comparison of contrast ratios in rectangular and triangular SEED devices has been completed.

Calculations of exciton transition energies, oscillator strength and modulator absorption ratios have successfully been performed for quantum wells having different profiles. The behavior of these structures as a function of electric field has also been performed. It was shown theoretically that asymmetric triangular quantum wells exhibit large contrast ratios at low electric fields.

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Spatial Light Modulators with Arbitrary Quantum Well Profiles

University Research Initiative Program
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ABSTRACT

This is the year 1 technical report for University Research Initiative (URI) program "Spatial Light Modulators with Arbitrary Quantum Well Profiles." During the first year of the program we have successfully grown GaAs/AlGaAs triangular and parabolic compositionally graded wells by solid source (SS) Molecular Beam Epitaxy (MBE) and gas source (GS) molecular beam epitaxy (GSMBE). In addition, strained InGaAs/GaAs wells have also been grown. An optimization of growth conditions for obtaining narrow exciton linewidths in square and nonrectangular wells was completed. We have refined the superlattice compositional grading technique to obtain 3 meV photoluminescence linewidths in a triangular quantum well.

A study of the optical properties has begun in which the structures are characterized by room temperature and 2K photoluminescence and photocurrent spectroscopies. Responsivity curves for structures having various well shapes have shown the excited states and a comparison with theory is in progress. A preliminary comparison of contrast ratios in rectangular and triangular SEED devices has been completed.

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A. Statement of work

As stated in the original proposal, specific tasks to be performed during year 1 are listed below. The progress during the year has been briefly described accordingly. Details can be found in the next section.

The following acronyms are used for brevity throughout this report:

SQW	single quantum well
MQW	multiple quantum well
RQW	rectangular quantum well
CQW	coupled quantum wells
ATQW	asymmetric triangular quantum well
STQW	symmetric triangular quantum well
APQW	asymmetric parabolic quantum well
SPQW	symmetric parabolic quantum well

Year 1

1 Experiment

- Grow rectangular AlGaAs/GaAs MQW structures optimized for sharp interfaces.

A considerable amount of effort has been dedicated toward the goal of achieving a high degree of heterojunction interface abruptness. The On/Off ratio of a spatial light modulator (SLM) operating via excitonic absorption and the quantum confined Stark effect (QCSE) is very dependent on the exciton linewidth of the optical transitions. We have grown GaAs/AlGaAs quantum wells with the following 2K photoluminescence linewidths:

GaAs/AlGaAs

SS MBE	85Å	1meV	SQW & MQW 10 periods
GS MBE	100Å	0.61 meV	SQW
		0.74 meV	MQW 40 periods
ATQW	200Å	3.13meV	SQW
		3meV	MQW 10 periods

Best GaAs/AlGaAs results from literature:

Ploog[1] (SS)	120Å	0.56 meV	SQW
Bhattacharya[2] (SS)	120Å	0.8 meV	SQW
Bhattacharya[2] (SS)	120Å	0.3 meV	SQW (with superlattice barriers)

InGaAs/GaAs (SS-ASU)

RQW	50Å	2 meV	SQW x=0.15
ATQW	200Å	3 meV	SQW x=0.15

* Characterize by optical and electrical techniques.

Low temperature PL and photocurrent spectroscopy are routinely used to measure the optical transitions of the ground and excited states quantum wells. The behavior of these levels has been experime measured as a function of electric field and temperature.

* Grow coupled rectangular wells.

Two sets of coupled quantum wells have been grown and are awaiting tes

* Fabricate spatial light modulators from the MQW structures optimiz ON/OFF ratio.

Spatial light modulators and waveguide modulators have fabricated by photolithography, e-beam metallization and chemical and re ion etching. A revision of the original design has been complete implemented. Contrast ratios for our devices have been obtained.

* Develop semi-parabolic well growth techniques.

The compositional grading technique has been refined and implem to grow different parabolic well test structures.

In addition to the year 1 tasks, we have addressed some tasks sp in year 2. These are:

* Develop growth techniques for parabolic wells and asymmetric li graded wells.

The compositional grading technique has been refined and implem to grow both symmetric and asymmetric quantum well structures. B .h ty composition profiles have been realized.

* Develop process for growing asymmetric triangular and sym triangular wells.

See previous item.

* Simultaneously grow AlGaAs-InGaAs-GaAs pseudomorphic structu

Strained InGaAs/GaAs quantum wells have been grow characterized. These exhibit very high luminescence efficiency and narr linewidths.

* Attempt to grow structures by gas source MBE.

GSMBE ATQW modulators have been grown and their PL line compare to those grown by solid source MBE.

Here n_0 is the index of refraction and the lineshape $\Delta(x)$ is assumed to be a Lorentzian given by

$$\Delta(x) = \left(\frac{\Gamma}{\pi}\right)\frac{1}{(x^2+\Gamma^2)}$$

having a width Γ.

The excitonic energy shift as a function of applied electric field determines the operating performance of an absorptive modulator. Thus it is necessary to compute the absorption ratio versus electric field. This is accomplished simply by normalizing the absorption to the zero field absorption value or $\alpha(F)/\alpha(F=0)$.

To summarize the results of the calculations we present a comparison of three AlGaAs/GaAs modulators consisting of different quantum well profiles all operating at a photon energy of 1.572 eV. Compared are a rectangular well (L_W= 75Å), an asymmetric parabolic well (L_W= 174Å) and an asymmetric triangular well (L_W= 676Å). Figures 1a, 1b and 1c show the calculated absorption ratios versus electric field in the device. The curves in each figure are for different values of exciton transition linewidth in meV. The reduction in electric field required to modulate the device for small exciton linewidths is evident.

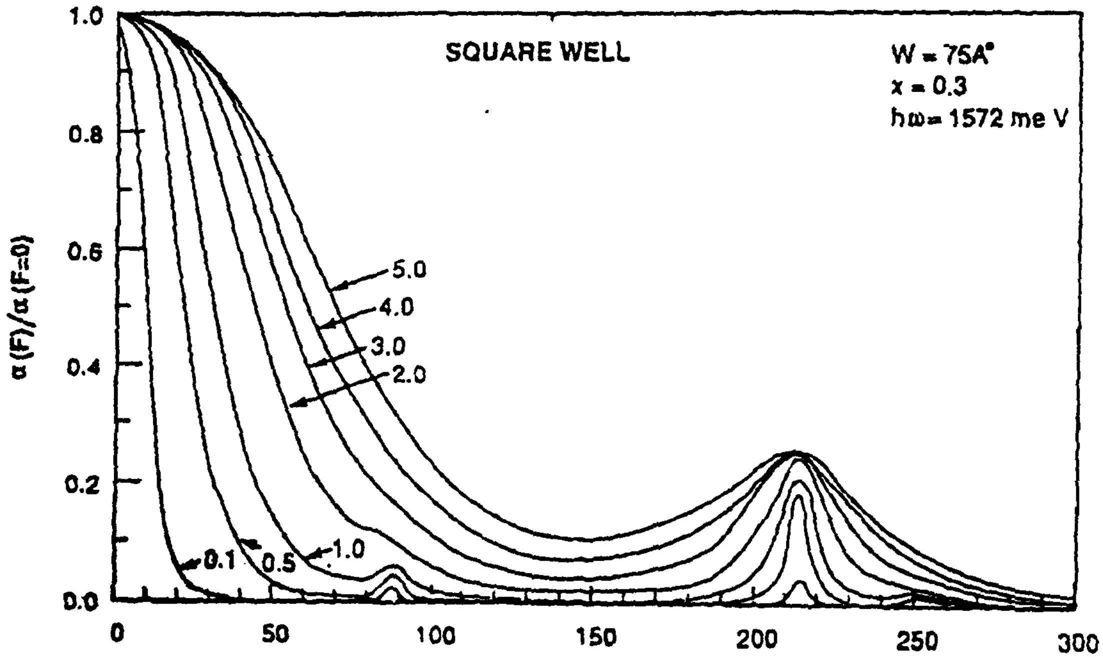

Figure 1a. Variation of absorption ratio at 1572 meV as a function of electric field and exciton linewidth (meV) for a square well.

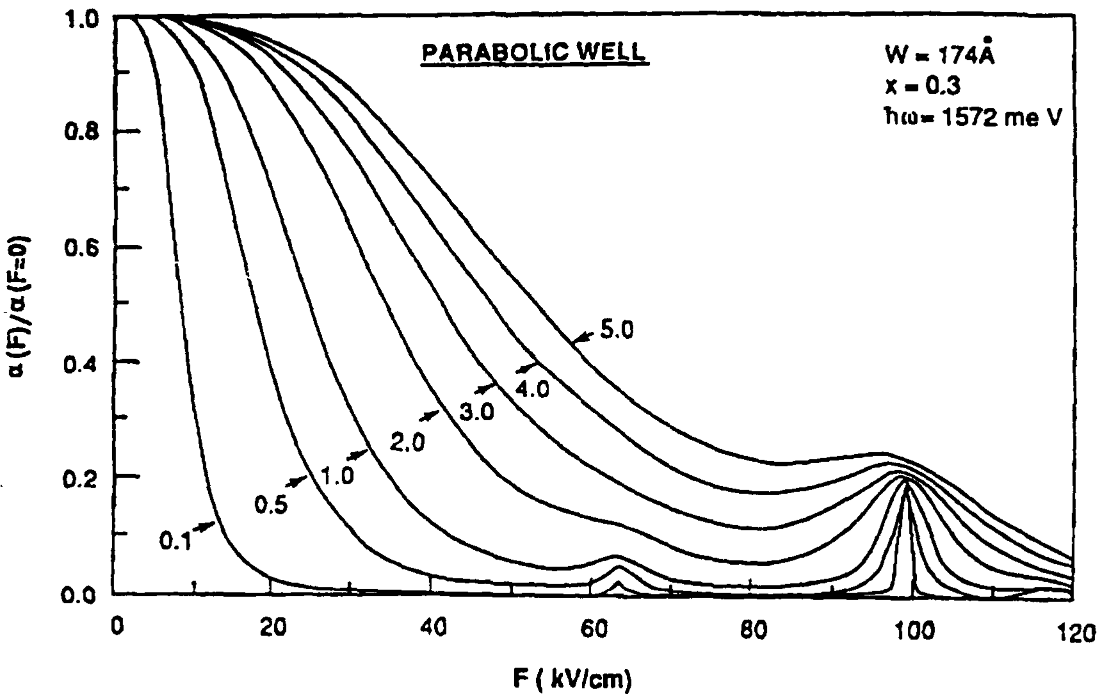

Figure 1b. Variation of absorption ratio at 1572 meV as a function of electric field and exciton linewidth (meV) for an asymmetric parabolic well.

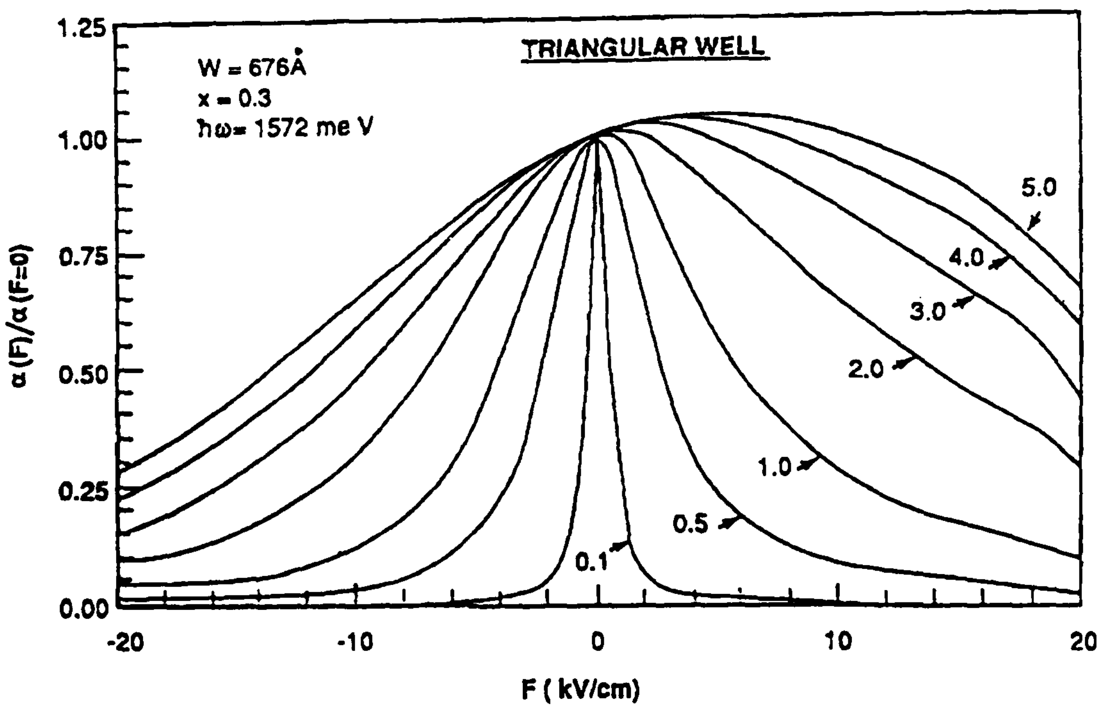

Figure 1c. Variation of absorption ratio at 1572 meV as a function of electric field and exciton linewidth (meV) for an asymmetric triangular well.

In the case of the square well, application of relatively large fields are required to achieve significant changes in the absorption ratio due to the small well size. For a linewidth of 3meV, a field of approximately 50 kV/cm is required to achieve a 30 percent decrease in absorption. This corresponds to a voltage of 10 volts applied across a 2μm region.The corresponding field for the parabolic well is 7 volts at a field of 35 kV/cm. The asymmetric triangular well, however, requires only 1.4 volts for an applied field of -7kV/cm.

This behavior is due to the fact that the triangular well is the widest of the three cases and thus the separation of the electron and hole charge distributions is greater for a given applied electric field. The absorption coefficient is thus a stronger function of electric field in this case. The calculated contrast ratio (On/Off ratio) at -20kV/cm is approximately 6.7 for the triangular well as compared to 1.02 for the corresponding triangular well.

In conclusion, triangular well modulators have the potential to achieve high contrast ratios at low applied voltages thus making them useful for integration with other devices. A model following the previous analysis is presently being developed for a parabolic modulator.

A new approach to treating excitons in quantum wells is currently being developed. The effects of the Coulomb potential in the xy planes are calculated first and then the solution for bound states in the z direction is obtained. A variational wavefunction with an appropriately modified Hamiltonian is used to solve the Schrödinger equation.

The new approach has the advantages that a more accurate value for the oscillator strength is obtained. Also because the potential variation in the z direction due to the quantum well potential and applied field have no effect on the translational symmetry of the Hamiltonian in the xy plane, the eigenvalues and eigenfunctions in the xy plane need only be obtained once.

2 Experimental realization of nonrectangular quantum well modulators

This section describes the MBE growth of nonrectangular quantum wells by the superlattice compositional grading technique. The quantum well structures have been optimized for narrow linewidth and electro-optic devices fabricated and tested. An additional application of the superlattice compositional grading technique to vertical cavity surface emitting lasers (VCSEL) is also mentioned.

a. MBE growth of graded quantum wells

Accurate, controllable semiconductor alloy compositional grading over distances of approximately 100 Å poses some problems to the MBE crystal grower. There are two approaches to this problem. The first is to change the group III flux as a function of time to achieve a continuously grading. Because of the long thermal time constant in solid source effusion cells, this was not deemed to be a practical approach in order to obtain a high degree of control. The second method is to approximate a particular alloy composition in a thin region by averaging the thicknesses of two different alloy compositions. In quantum wells, the averaging must be performed in regions (or cells) of total thickness of approximately nine monolayers (ML) to obtain sufficiently fine gradations of the alloy compositions to approximate, for instance, a linear profile. Hence, the use of a superlattice consisting of unequal barriers (or wells) must be grown. This discrete multilayer structure could be considered formed by a "digital" grading technique as opposed to the continuously changing flux method ("analog"). The experimental realization of such a structure is shown in figure 2. Shown here is an example of an asymmetric triangular quantum well of approximately 260Å width. It consists of alternating GaAs and $Al_{0.3}Ga_{0.7}As$ layers grading the composition from x=0 at the well bottom to x=0.3 at the barriers. The transmission electron micrograph of the ATQW is on the left showing the discrete superlattice layers schematically depicted in the center figure. At the far right is the approximate conduction band energy profile showing the desired triangular potential well and two quantum well confined electron states. The next section describes the experimental verification of these states by optical techniques.

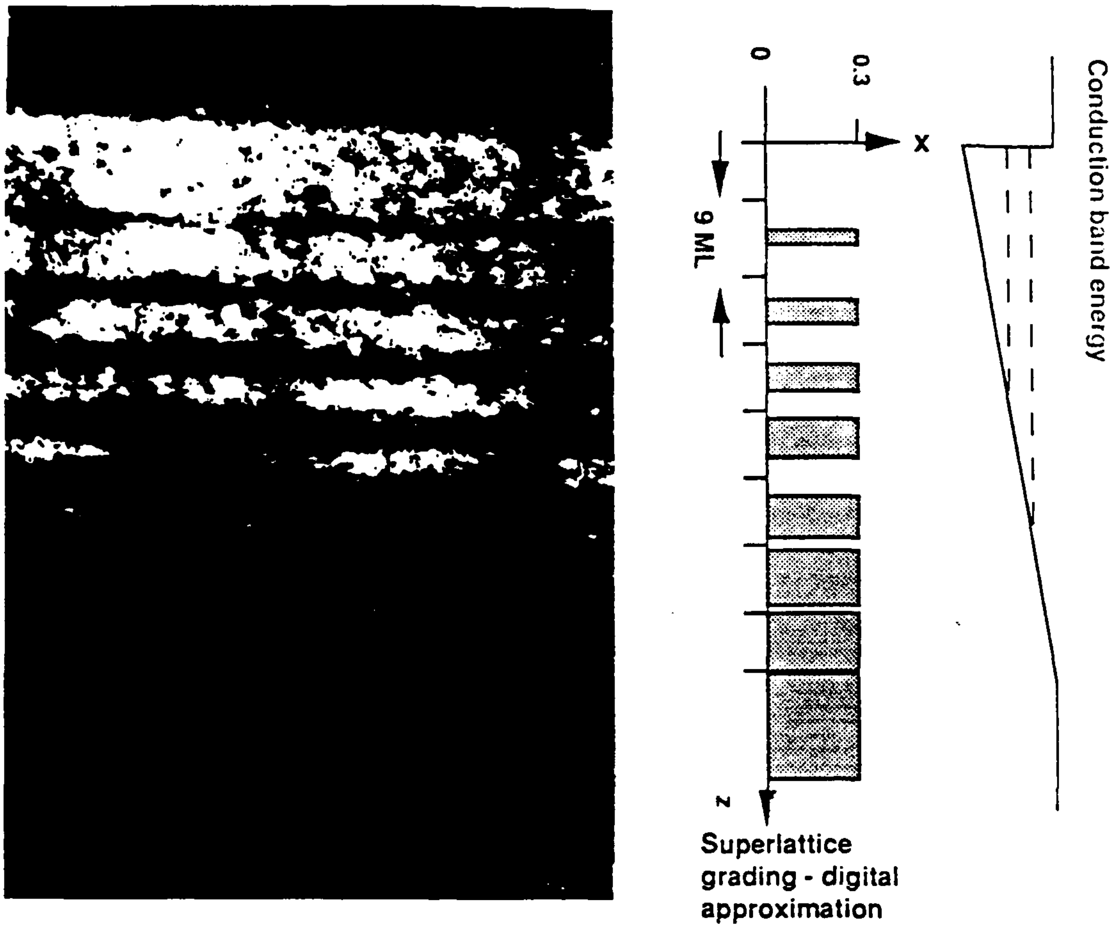

Figure 2. Transmission electron micrograph (TEM) of a 260Å asymmetric triangular quantum well (left) consisting of GaAs/AlGaAs compositionally doped superlattice in which a unit cell of approximately 25Å has been used. On the right is a schematic showing the superlattice compositional grading structure and corresponding conduction band energy profile.

Typically a 9 ML superlattice cell is used in order to obtain a fine gradation of the alloy composition. High resolution transmission electron microscope (TEM) lattice imaging has shown that the heterointerfaces are extremely abrupt. Interface abruptness is important to achieve narrow photoluminescence linewidths in order to produce modulators with high contrast ratios. A significant portion of the effort has been dedicated to optimizing growth conditions to achieve the narrow linewidths required for high contrast ratio optical modulators. These results are described in the next section.

All MBE structures were grown at ASU in a Vacuum Generators (VG) V80-H MBE system. This system consists of two growth chambers; one for solid source (SS) growth and the other for gas source (GS) growth of III-V semiconductors. As_2 is generated in the GSMBE by pyrolysis of arsine in a low

pressure cracker. We have used this system to grow nonrectangular quantum wells both by SSMBE and GSMBE as described in later sections.

b. Optimization of PL quantum well linewidth

As previously shown, the contrast ratio in a modulator is very dependent on the excitonic transition linewidth. Hence, growth optimization for narrow PL linewidth was necessary. Square well linewidths were initially used as the gauge for our growth process because sufficient results were available in the literature with which to compare. In our system, linewidths of 1 meV were realized both for a single well and a 10 period MQW grown by SSMBE. The best reported values that we are aware of are 0.56 meV (Ploog[1]) and 0.8 meV (Bhattacharya[2]). A linewidth of 0.3 meV for a single quantum well with superlattice barriers was also obtained by Bhattacharya[2]. In parallel, we grew square QWs by GSMBE with linewidths of 0.61 meV and MQWs with FWHM = 0.74 meV. This is presently the record narrowest linewidth achieved by GSMBE. The results can most likely be improved but are sufficient for the fabrication of the devices in this program.

A point of clarification should be mentioned before proceeding. Several ATQW structures are presented in this section. At the present time there are three different methods of determining the ATQW width. These are 1) theoretical fitting of the photoluminescence ground state transition energy, 2) determination of thickness by growth rate calibration and 3) direct thickness determination by high resolution transmission electron microscopy (TEM). The TEM data is the most accurate measure because individual atomic planes can be counted to obtain QW thicknesses. At the present time, we do not have TEM micrographs of all our samples to make direct comparisons and thus identify the well widths by their values determined by growth rate calibration. These are identified as "nominally 200Å" for example to indicate the approximate design values. As will be seen, there is a discrepancy among all of the techniques which arises from difficulties in the growth of submonolayer structures and non-ideal composition profiles. These discrepancies are presently the basis of much effort. We have made progress in this comparison because we have obtained the first TEM pictures of the ATQW structures.

Asymmetric triangular quantum wells were then grown for optical evaluation. Figure 3 shows the 2K PL data of a "nominally" 200 Å MBE ATQW exhibiting a linewidth of approximately 4 meV. The narrowest linewidth that we have obtained for an ATQW is actually less than this (3.13 meV). Hence we have demonstrated that the superlattice compositional grading technique can be used to realize nonrectangular quantum wells with narrow linewidths. Effort will continue toward further decreasing this linewidth in order to obtain the best possible device properties. Calculations of the theoretical minimum linewidth for nonrectangular QWs should be performed for comparison with the experimental data.

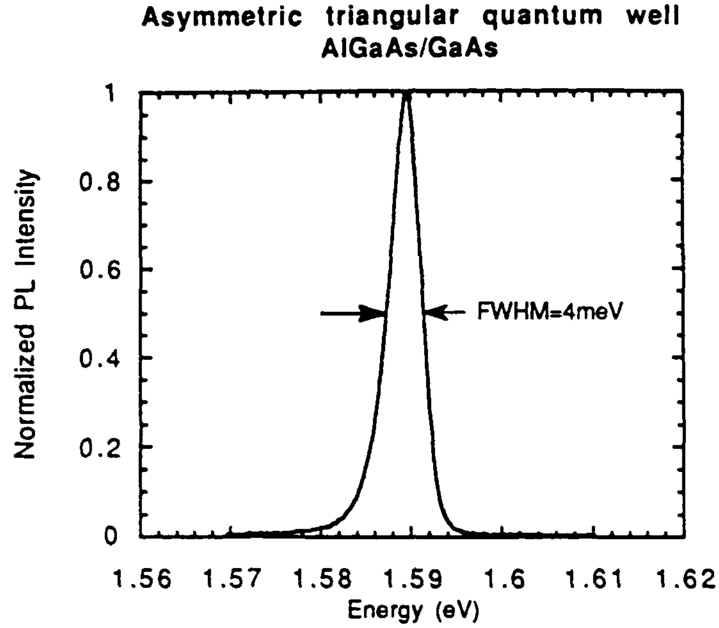

Figure 3. Typical photoluminescence of a "nominally" 200Å asymmetric triangular quantum well grown by MBE. The FWHM for this sample is approximately 4 meV. The TEM of figure 2 shows this to have a well width of 260Å. The theory calculates a width of approximately 400Å.

Growth of ATQWs was also performed by GSMBE. Figure 3a is a photoluminescence plot of a "nominally" 200Å ATQW grown by GSMBE. The linewidth is shown to be 3.6 meV which is approximately the same as that observed in the SSMBE grown structures. The main difference between the two is the low energy tail characteristic of the GSMBE material. This effect due to a higher background acceptor concentration which originates from the group V gas source. This can be reduced by additional scrubbing of the hydride source and also obtaining higher purity gas. Hydride purity is one of the main problems in GSMBE today and is being addressed by several chemical manufacturers. Nevertheless, we have optimized our growth conditions in both MBE and GSMBE to produce approximately the same high optical quality material for this program.

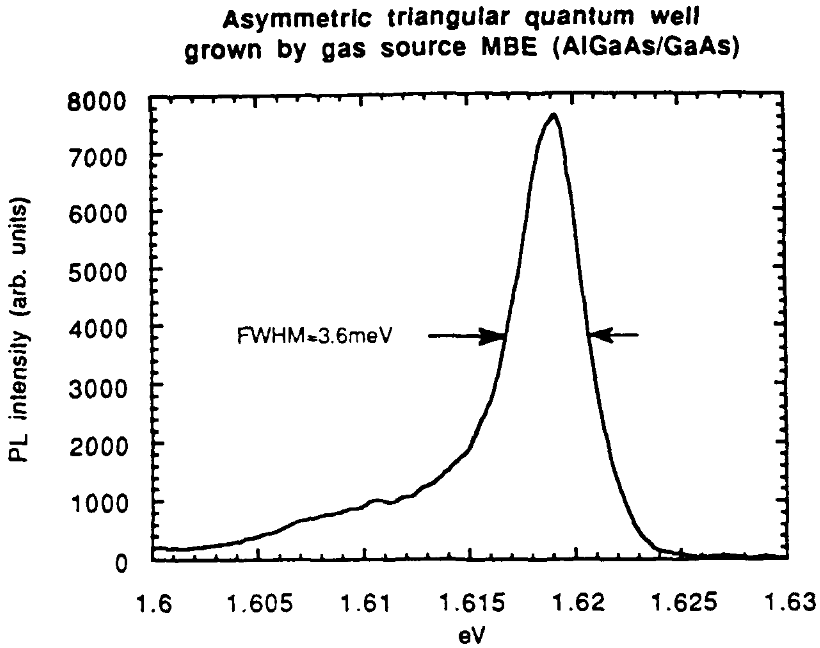

Figure 3a. Photoluminescence plot of a "nominally" 200Å asymmetric triangular quantum well grown by gas source MBE. The FWHM is 3.6 meV. No TEM is yet available for this sample. Theory calculates a well width of approximately 260Å.

The ground state transition in the SSMBE ATQW shown in figure 3 occurs at a lower energy than in the GSMBE ATQW in figure 3a even though they are grown "nominally" the same. The difference in energies could be explained by thickness variations and composition profile differences. We are presently attempting to resolve these technological problems and the large discrepancy between theory and experiment.

Optimization of strained InGaAs/GaAs QWs has also begun. The best results we have obtained so far are a 2K FWHM of 2 meV for a "nominally" 50Å $In_{0.15}Ga_{0.85}As$ RQW and 3 meV for a "nominally" 220Å ATQW. The InGaAs QW linewidth is slightly narrower than the equivalent AlGaAs/GaAs well. Work is presently directed toward understanding these properties.

c. Photocurrent spectroscopy

The theoretical calculations provide energies for all of the optical transitions in a quantum well of arbitrary shape. Photoluminescence only measures the ground state however. Photocurrent spectroscopy was implemented to determine the energies of all of the excited states in the well to make a direct comparison with the theoretical calculations.

In photocurrent spectroscopy the current in a device is measured as a function of optical excitation energy. There is a peak in the photocurrent (or optical absorption) when the energy of the incident photon is equal to an exciton transition energy in the quantum well. By tuning the incident photon

energy through the quantum well states, all optical transitions can thus be determined.

Figure 4 shows a typical photocurrent spectrum for an ATQW SEED structure (details are in device section). Six optical transitions between confined electron and hole states in the quantum well are labeled.

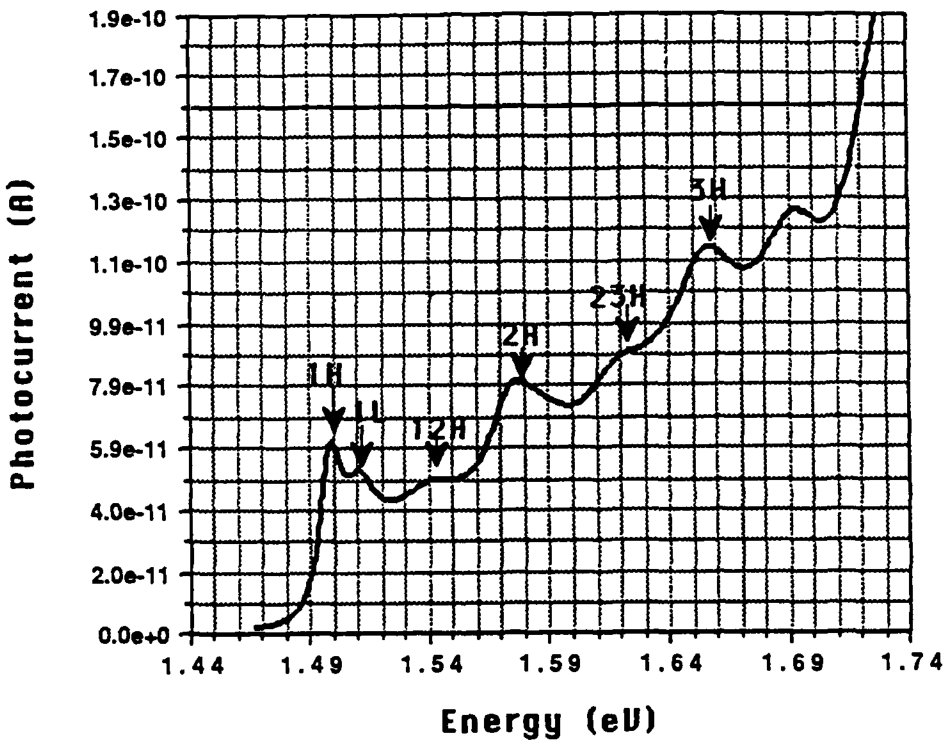

Figure 4. Photocurrent spectrum of an asymmetric triangular quantum well structure having well width of L_W = 240Å. Six excitonic transitions are identified.

There is reasonable agreement between the data shown and the theoretical calculations of this structure for the ground state. There is a divergence between theory and experiment for the higher excited states however which may be due to either the well profile not being exactly linear or an approximation in the theoretical model. Nevertheless, the agreement is sufficient to enable the design of nonrectangular well devices because the ground state is the dominant contributor to the contrast ratio. The differences between theory and experiment are presently being addressed.

d. Self electro-optic effect devices (SEED)

A SEED is basically a p-i-n structure whose intrinsic active region is a multiple quantum well. A typical AlGaAs/GaAs device structure is shown in

figure 5. The intrinsic active region is comprised of a multiple quantum well which can have any of the shapes described previously. Switching of the device is achieved by reverse biasing the p-i-n diode, which increases the electric field in the intrinsic region and shifts the exciton absorption edge by the quantum confined Stark effect (QCSE). The InGaAs QW modulator structure is identical except that the window in the n^+ GaAs substrate need not be etched. This is because InGaAs QW optical transitions are below the GaAs bandgap and thus photon absorption in the GaAs is minimal.

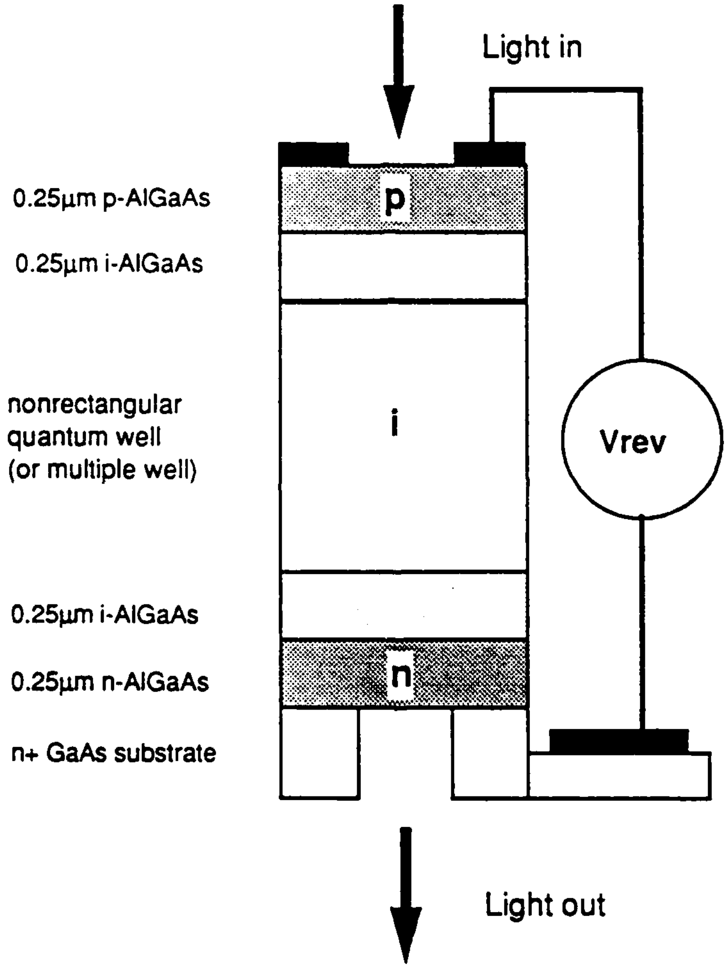

Figure 5. Generic self electro-optic effect device (SEED) p-i-n structure. The active region is an intrinsic multiple quantum well.

We are presently on the second iteration of prototype devices. The second mask set addressed some of the deficiencies in the first and included some additional test structures. Device active areas range from 10µm X 10µm to 100µm X 100µm. Figure 6 is a Nomarski photograph of several size devices fabricated with the new mask set. Device fabrication is done with photolithography, reactive ion and chemical etching and electron beam metallization. Several sets of working devices have been fabricated and are presently under investigation.

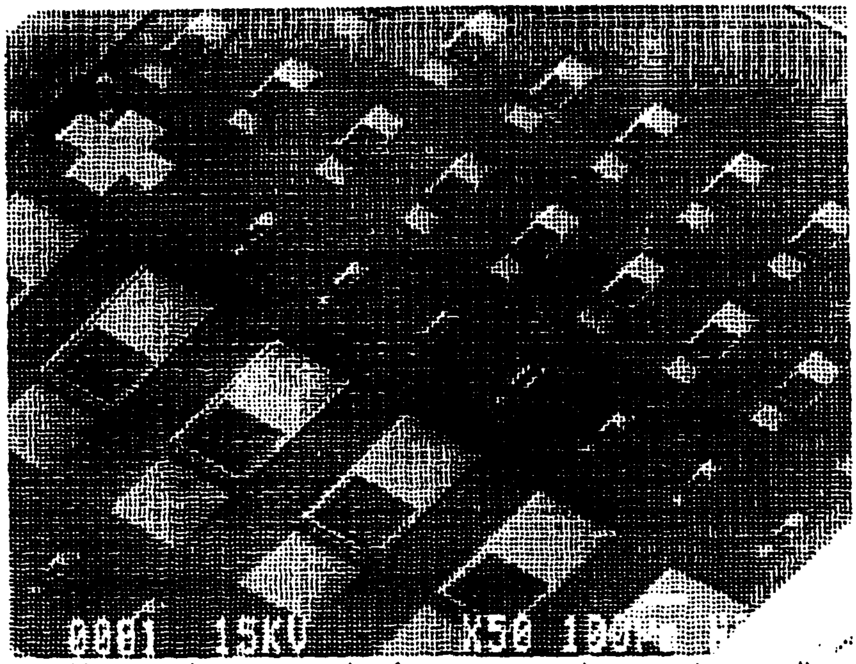

Figure 6. Nomarski photograph of nonrectangular quantum well modulators used in this study.

Figure 7 shows a typical ATQW SEED modulator operating characteristic. Plotted is the experimental data of responsivity versus wavelength at different operating voltages. The excitonic shift to lower energies as a function of electric field is clearly observed indicating the modulator operation. At higher applied electric fields the n=1 electron to heavy hole absorption decreases with respect to the higher energy ones as expected. An increase in the current at low energies is a result of the reverse bias leakage current in the diodes.

Comparisons with calculated responsivity curves show two main differences. The first is that the leakage current at low energies is not modeled. This could easily be included in the future. The second is that the theory calculates responsivity versus electric field while in the experiments it is measured versus voltage. In some early devices, the regions adjacent to the intrinsic quantum well region were not fully depleted and there was an offset in the excitonic shift versus voltage. This was observed as a zero energy shift before some threshold voltage. With the device layer optimization this problem has been reduced in the triangular well configuration. Optimization of the square well devices will be performed soon.

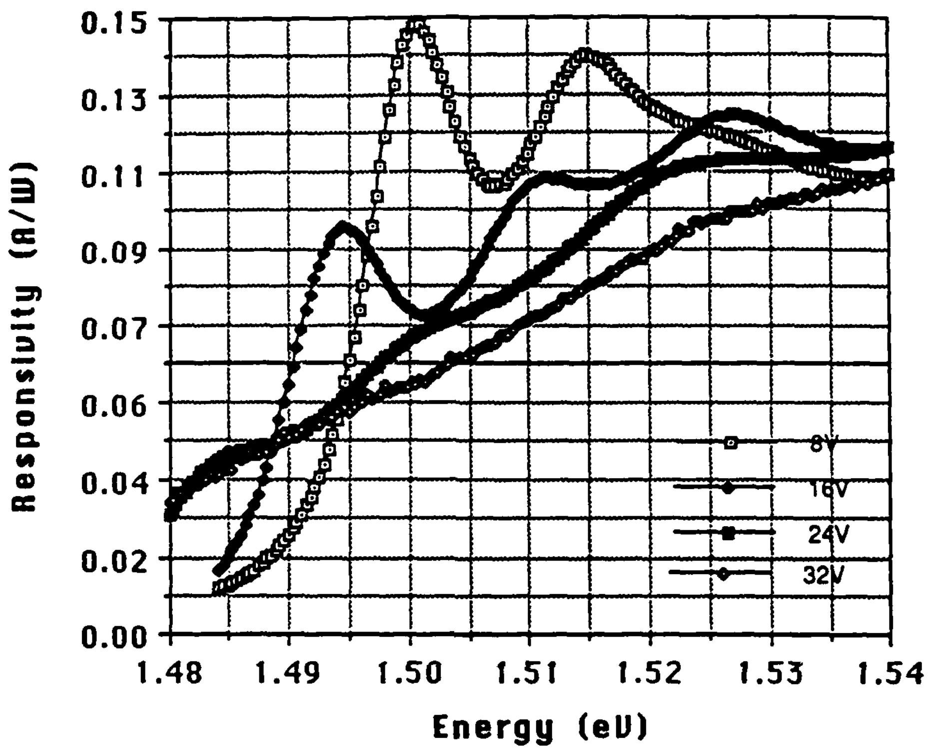

Figure 7. Responsivity versus wavelength for an asymmetric triangular quantum well modulator as a function of device bias. The excitonic transitions are shifted to lower energy with increasing electric field.

We have designed a spatial light modulator using asymmetrical triangular quantum wells. The device is a 10 period nominally 200Å ATQW modulator (not shown here) and has a maximum contrast ratio of 1.3 (for $V_{applied}$ = 16V) at an operating energy of 1.5108 eV. Work is in progress to compare optimized triangular well modulators with equivalent rectangular well modulators.

As previously mentioned, several device structures have been fabricated with different well shapes and widths. Now that the material growth, device fabrication and characterization have been brought online, we are in the process of making a set of devices with different well shapes all having the same transition energy and absorbing region thickness. This is for a direct comparison of contrast ration among devices with different well shapes and is expected to be completed early this spring.

e. Other research activities related to this project

As a test of our MBE growth of compositionally graded structures, we attempted the growth of an InGaAs vertical cavity surface emitting laser (VCSEL). This uses compositionally graded Bragg reflectors to reduce the electrical resistance of the mirrors toward the goal of reducing the threshold current density of the device. Because of the high optical efficiency of our InGaAs and because of the optimized superlattice compositional grading, we have achieved a record low threshold current density for a VCSEL of 487 A/cm^2 in continuous wave, room temperature operation.

3 Summary

In summary, we have made progress toward the stated goals during the first year of this program. MBE growth of compositionally graded quantum wells has been optimized to yield narrow photoluminescence linewidths. Rectangular, triangular, and parabolic shaped wells have been grown in the GaAs/AlGaAs material system. Growth of strained InGaAs/GaAs quantum wells has also been optimized. SEED devices have been fabricated from all of these well profiles. Their electrical and optical properties have been tested. The theoretical calculation of transition energy and oscillator strength versus electric field for different values of exciton transition linewidth and quantum well width has been completed. Models of spatial light modulators having different well shapes and sizes are in under way. Work is in progress to directly compare the theoretical calculations with the experimental data.

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[1] K. Ploog, A. Fischer, L. Tapfer and B.F. Feuerbacher, MBE VI Conference Proceedings 1990, to appear in JVST 1991.

[2] F.Y. Juang, Y. Nashimoto and P.K. Bhattacharya, J. Appl. Phys., **58**(5), pp. 1986-1989, (1985)

C. Publications in technical journals

R. Droopad, R. A. Puechner, K. T. Shiralagi, K. Y. Choi, G. N. Maracas, "Optical Properties of a Single Strained InGaAs/GaAs Quantum Well on Vicinal GaAs Surfaces," to be published in Appl. Phys. Lett., April 22, 1991

R.A. Puechner, D.S. Gerber, D.A. Johnson, R. Droopad and G.N. Maracas, "Optical Properties of Asymmetric Triangular Quantum Wells for Self Electro-optic Effect Devices," (invited paper) to be published in Journal of Nonlinear Optics 7/91

R. Droopad, R. Puechner and G.N. Maracas, Optical Properties of Strained Asymmetric Triangular InGaAs/GaAs Multiple Quantum Wells, submitted to Appl. Phys. Lett. 2/91

G.D. Sanders, G. N. Maracas and K. K. Bajaj,"A Numerical Model of the Quantum Well Waveguide Spatial Light Modulator" submitted to J. Quantum Electronics. (Sept 1990) Not accepted

G.D. Sanders and K.K. Bajaj, "Absorptive Electro-Optic Spatial Light Modulators with Different Quantum Well Profiles," J. Appl. Phys., **68**(10), pp. 5348-5356, (1990)

C. Gaw, M. Lebbe, G. N. Maracas and R. Droopad, "Strained Quantum Well Vertical Cavity Surface Emitting Lasers with Low Threshold Current Densities". Prepared but not submitted

D. Professional personnel associated with the research effort

G.N. Maracas, PI
R. Droopad, Assistant Research Scientist
Calvin Choi, Assistant Research Scientist
Don Gerber, PhD student
Ron Puechner, MS student
Gary Sanders, Faculty Associate (1/15/90 - 8/15/90)
Xi Zhang, MS student - MS student

K.K. Bajaj, PI
Emory postdoc
Emory student

E. Interactions:

Telephone conversations with AFOSR staff have been on a regular basis to discuss technical and contractual issues and developments. Preliminary data has also been sent to assist in program review during the year. One visit was made to AFOSR in July to discuss program developments.

1 Papers presented at meetings, conferences, seminars, etc.

R.A. Puechner, D.S. Gerber, D.A. Johnson, R. Droopad and G.N. Maracas, "Optical Properties of Asymmetric Triangular Quantum Wells for Self Electro-optic Effect Devices," Proceedings of IEEE Nonlinear Optics: Materials, Phenomena and Devices, Kauai, Hawaii (1990).

D.S. Gerber, R.A. Puechner, G.D. Sanders, R. Droopad, G.N. Maracas and K.K. Bajaj, "Effects of an Electrical Field on Excitons in MBE-Grown Nonrectangular Quantum Wells". Submitted to International Symposium on GaAs and Related Compounds, Jersey, UK 1990, not accepted

2 Consultative and advisory functions to other laboratories and agencies

F. New discoveries, inventions, or patent disclosures and specific applications stemming from the research effort.

An application of the MBE compositional grading technique to vertical cavity surface emitting lasers was described in section 2e.

G. Other statements